

QCD AND DIFFRACTION AT HERA

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Recent measurement of inclusive processes and hadronic final states in diffractive deep-inelastic scattering at HERA are used to investigate the QCD factorisation properties and study partonic structure of colour singlet exchange. Resolved Pomeron and colour dipole models are tested by comparison with the data.

1 Introduction

The observation of events with a large rapidity gap in the hadronic final state at HERA¹, which are attributed to diffractive dissociation of virtual photons, led to a renewed interest in the study of the underlying dynamics of diffraction. Diffractive scattering is governed by the exchange of the Pomeron (\mathbb{P}), an object carrying vacuum quantum numbers. Pomeron exchange was introduced in Regge theory² to describe the high energy behaviour of total hadron cross sections³, which are related to elastic scattering through the optical theorem.

In perturbative QCD (pQCD) the vacuum exchange is modeled as a colour singlet exchange of at least two gluons⁴ that develops into a gluon ladder between the photon and the proton. pQCD calculations are possible for diffractive processes where a hard scale is present: production of high mass quarks, high momentum jets, processes with high virtuality Q^2 or squared four-momentum transfer t .

At HERA, by changing Q^2 and t , it is possible to vary the resolution with which the Pomeron structure is probed in diffractive interactions, and to study its partonic content. HERA is thus an unique facility to study the transition from soft to hard interactions.

The kinematics of diffractive deep-inelastic scattering $ep \rightarrow eXp$ can be expressed in terms of the variables Q^2 , t , Bjorken x and the invariant mass of the X system - M_X . In addition, the variables $x_{\mathbb{P}}$ and β are introduced. In the proton infinite momentum frame, $x_{\mathbb{P}}$ is the fraction of the beam proton momentum carried by the Pomeron, β is the fraction of the Pomeron momentum carried by struck parton.

2 Factorisation and diffractive parton distributions

It has been proven that in diffractive ep processes diffractive structure function F_2^D factorises into long and short distance contributions in analogy with the inclusive F_2 (QCD factorisation), i.e.

$$F_2^{D(4)}(\beta, Q^2, x_{\mathbb{P}}, t) \sim f^D(\beta, Q^2, x_{\mathbb{P}}, t) \otimes \hat{\sigma}(\beta, Q^2) \quad (1)$$

where $\hat{\sigma}$ are cross sections for pQCD hard scattering and f^D are diffractive parton density functions (PDFs), which express conditional proton parton probability distributions at fixed $x_{\mathbb{P}}$ and t . The PDFs obey the DGLAP evolution equations and are universal for diffractive DIS processes (inclusive, jet, charm production)⁶.

If for all relevant f^D , the $x_{\mathbb{P}}$ and t dependences decouple from the β and Q^2 dependences, the extended factorisation property is known as Regge factorisation or the "resolved Pomeron" model⁷:

$$F_2^{D(4)}(\beta, Q^2, x_{\mathbb{P}}, t) = \Phi(x_{\mathbb{P}}, t) \cdot F_2^{\mathbb{P}}(\beta, Q^2) \quad (2)$$

In this case $\Phi(x_{\mathbb{P}}, t)$ can be interpreted as the flux of the Pomeron, and $F_2^{\mathbb{P}}$ as the structure function of the Pomeron. The flux factor describes the long distance physics at the proton vertex, while the structure function depends on the exchanged parton densities and the short distance physics at the photon vertex.

In the complementary "colour dipole" approach the virtual photon is considered to fluctuate into $q\bar{q}$ or $q\bar{q}g$ states described by dipole wave functions⁸. In the proton rest frame and at low Bjorken x the fluctuation happens long before the interaction with the proton. The diffractive γ^*p cross section is factorised into the square of the effective dipole wave function and the square of the cross section for the diffractive scattering of the dipole off the proton. The dipole cross section can be calculated in pQCD for relatively small dipole sizes, corresponding to high values of Q^2 . There are several "colour dipole" models which differ in the way they treat the actual dipole-proton interaction^{8,9,10,11}.

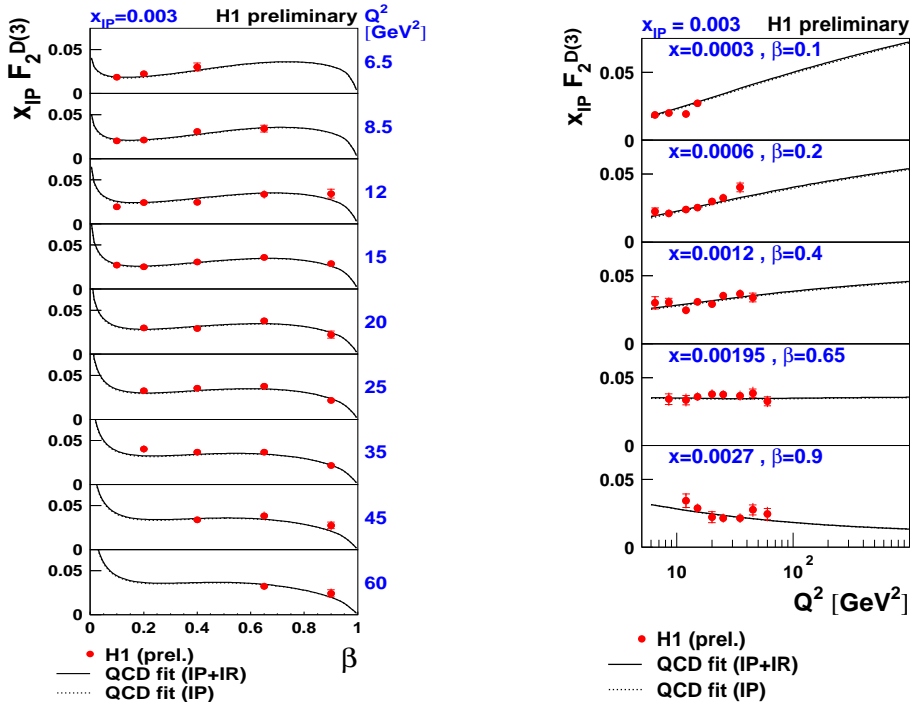


Figure 1: The diffractive structure function $x_{\mathbb{P}} F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}})$ plotted as a function of β and as a function of Q^2 at fixed value of $x_{\mathbb{P}} = 0.003$. Also shown is the result of a QCD fit to the data.

H1 Diffractive Dijets

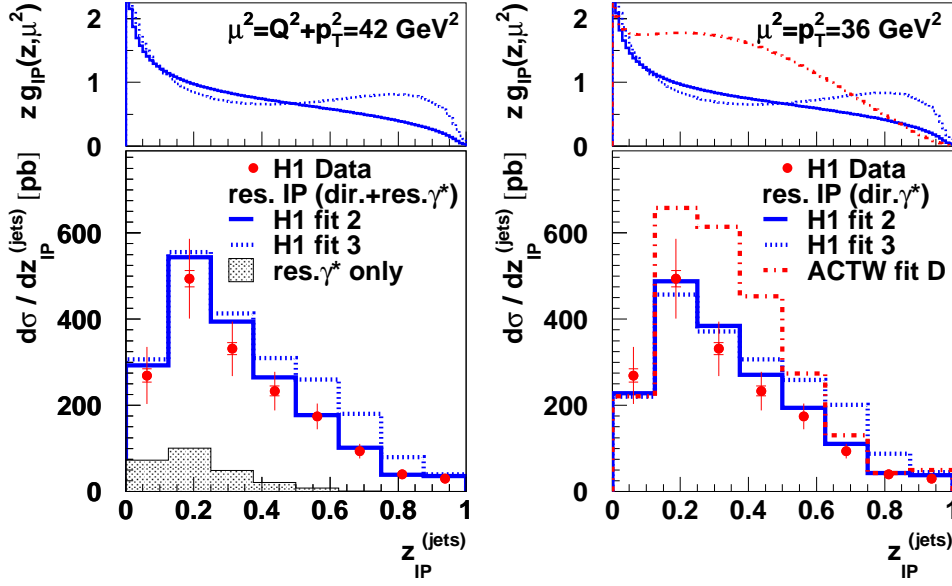


Figure 2: The diffractive dijet cross section as a function of $z_{\mathbb{P}}$ compared with predictions of the "resolved Pomeron" model based on the QCD fits. The diffractive gluon densities for each fit are shown above the data at the mean scale p_T^2 or $Q^2 + p_T^2$.

The $x_{\mathbb{P}}$, β and Q^2 dependence of $F_2^{D(3)}$ is studied in a new high precision measurement by the H1 experiment¹³. The measured structure function integrated over $|t| < 1 \text{ GeV}^2 x_{\mathbb{P}} F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}})$, shown in Fig. 1 for a fixed $x_{\mathbb{P}}$ value, indicates a rising scaling violation with $\ln Q^2$, persisting up to relatively large value of $\beta \sim 0.65$. At the highest β , the F_2^D scaling violation becomes negative. In this region, higher twist contributions such as vector meson production could play a major role in the diffractive cross section¹⁰.

A fit assuming both QCD⁶ and Regge factorisation⁷ was performed in which the parton densities in the Pomeron were evolved according to the leading order DGLAP equations. The fit result is compared with the data in Fig. 1. The logarithmic scaling violation in Q^2 and relatively flat β dependence is described by the fit, which predicts a partonic momentum distribution of the Pomeron dominated by a gluon contribution extending to large fractional momenta.

3 Diffractive dijet and charm production

According to the QCD factorisation theorem⁶, parton distributions extracted from the QCD fits to inclusive diffraction can be used to describe to hadronic final states in diffractive DIS for the same $x_{\mathbb{P}}$ and t . Of particular interest are measurements of diffractive dijet and open charm production, since the implied boson gluon fusion process $\gamma^* g \rightarrow q\bar{q}$ provides a direct probe of the gluon content of the Pomeron. The presence of the hard scale, provided by the high momentum jets or mass of the charm quark, allows a variety of perturbative QCD-based models of diffraction to be tested.

In Fig. 2 the quantity $z_{\mathbb{P}}^{jets}$ representing the fraction of the hadronic energy in the final state contained in the two jets of a high p_T jet sample, is compared with the prediction from the "resolved Pomeron" model⁷ based on different sets of Pomeron gluon distributions obtained from the leading order DGLAP fit of earlier $F_2^{D(3)}$ data by the H1 experiment⁵ and others¹².

The data favour the Pomeron dominated by gluons with a gluon momentum distribution that is relatively flat in $z_{\mathbb{P}}^{jets}$. For diffractive scattered $q\bar{q}$ photon fluctuations, a distribution peaked at $z_{\mathbb{P}} \sim 1$ is expected. The low values of $z_{\mathbb{P}}$ correspond to dominance of $q\bar{q}g$ over $q\bar{q}$ scattering. The $x_{\mathbb{P}}$ and β distributions of the dijet cross section are in agreement with the "resolved Pomeron" model with the

Pomeron intercept $\alpha_{\mathbb{P}}(0)$ extracted from inclusive $F_2^{D(3)}$ data⁵. In the "colour dipole" approach the model which allows non-ordered k_T distribution of the partons⁹ gives good description of the dijet data whereas the model with strong k_T ordering ($k_T^g \ll k_T^q$)¹⁰ is much below the data. The result indicates that non-ordered k_T contributions could be important in diffractive dijet production.

The "resolved Pomeron" model with various assumptions for the partonic composition of the colourless exchange^{5,12} provides a reasonable description of the diffractive D^* production measured by the H1 and ZEUS experiments^{14,15}. Predictions of two gluon exchange "colour dipole" models^{9,10,11} match the H1 data at low $x_{\mathbb{P}}$ and describe the ZEUS data except for the β distribution. Higher statistics of diffractive D^* events are needed to distinguish between the models.

4 Event shapes and three jet production

The properties of the diffractive hadronic final state were studied recently by the ZEUS experiment in terms of global event-shape variables such as thrust in the center-of-mass (CMS) frame¹⁶. For collimated two-jet $q\bar{q}$ events the value of thrust approaches 1, while events with an isotropic shape yield values close to 0.5. $q\bar{q}g$ final states are therefore expected to yield thrust values lower than $q\bar{q}$. In Fig. 3(left) the thrust distribution is shown as a function of the invariant mass M_X of the hadron final state. The diffractive hadronic final state becomes more collimated as M_X increases, a tendency also observed in e^+e^- annihilation. The diffractive events show a thrust distribution which is shifted to low values compared with processes $e^+e^- \rightarrow q\bar{q} \rightarrow \text{hadrons}$, indicating that they are more isotropic. This can be attributed to contributions not present in e^+e^- annihilation, such as the boson-gluon fusion process in the "resolved Pomeron" approach⁷, or $q\bar{q}g$ production from the dissociation of the virtual photon in the "colour dipole" approach⁸.

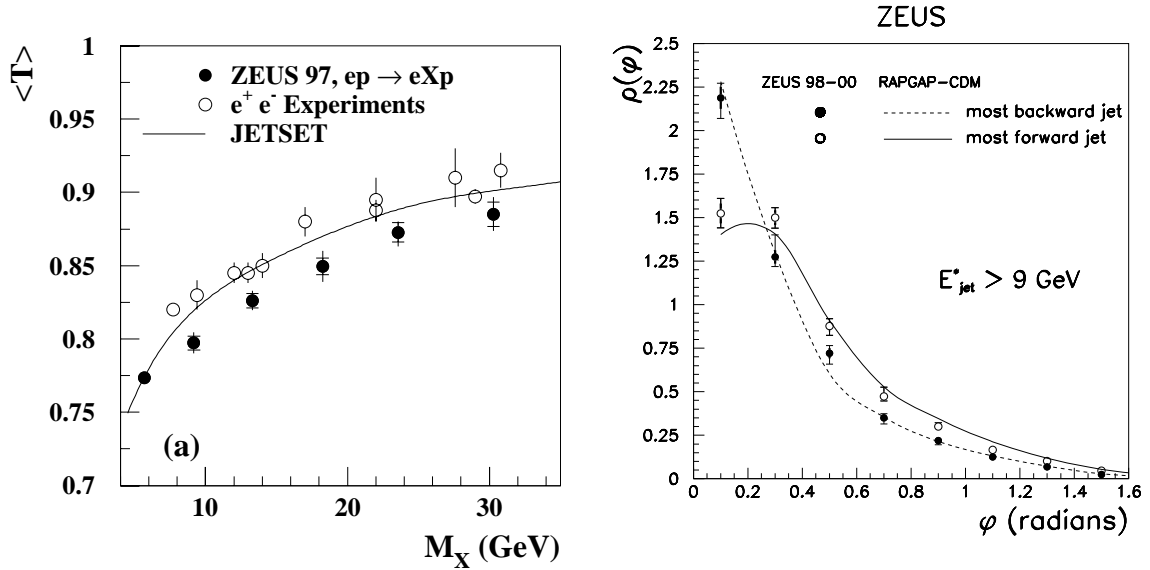


Figure 3: **Left:** Average thrust $\langle T \rangle$ of the diffractive DIS hadronic final state as a function of M_X . **Right:** The differential jet shape $\rho(\phi)$ for the most-forward and most-backward jets in three-jet events, where the Pomeron defines the forward direction

Diffractive three jet events were studied by the ZEUS experiment¹⁷. The differential jet shape $\rho(\phi)$, defined as the fraction of the jet energy which lies inside annulus at angular distance ϕ around the jet axis, is shown in Fig. 3(right) as a function of ϕ for the most-forward and most-backward jet. The forward direction is defined by the Pomeron, the backward direction - by the virtual photon. The jet in the Pomeron direction is broader than the jet in the photon direction. This measurement supports the picture where three jet final state is dominated by $q\bar{q}g$ configuration with a gluon emitted in the Pomeron direction. The jet shape distribution is reproduced by the "resolved Pomeron" model with the Pomeron dominated by gluons^{7,5}.

5 Summary

A consistent picture of inclusive diffraction and hadronic final states is observed in DIS at HERA. The F_2^D and dijet measurements support QCD factorisation with diffractive parton density functions dominated by gluon contribution. Event shape distributions and the topology of three jet events also indicate a significant contribution of $q\bar{q}g$ systems in final state the with gluon emitted in the Pomeron direction. A variety of diffractive DIS data are successfully described by the "resolved Pomeron" model in the proton infinite momentum frame and "colour dipole" models in the proton rest frame.

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